Event Location and Characterisation

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Grant: F49620-94-1-0110
Sponsored by: ARPA

ABSTRACT

The accurate location and subsequent characterisation of seismic events is a primary requirement of any verification regime for a test ban treaty. Such procedures depend on the use of good models for the propagation of seismic waves and also accurate picks for identified seismic phases.

An improved radial model of Earth structure has been developed, model *ak135* which provides a very good fit to the empirical travel times for a wide range of seismic phases. The improvements in fit to *S* phases and core phases compared with *iasp91* or *sp6* should improve the accuracy of location procedures exploiting later phases. This representation of the major contribution to teleseismic arrivals needs to be supplemented by correction procedures to allow for the main sources of lateral heterogeneity within the Earth. Ellipticity corrections have been developed for the *ak135* model for a very wide range of phases. A regionalised model for upper mantle corrections is under development as part of a hierarchical scheme of corrections to allow for different influences on the travel times of a wide range of seismic phases.

Precision location requires a good representation of the Earth and also accurate and correctly identified time picks for seismic phases. We have been developing automatic phase detection and recognition procedures which can help with the association of seismic arrivals for use in the location procedures. A pattern recogniton approach has allowed the extraction of phase wavelets whose character can be recognised through the interaction of a number of energy measures applied to three component waveforms.

Subsequent activity will be directed to try to improve the estimation of the depth of seismic events by integrating knowledge of waveform characteristics with estimation of source character.

Keywords

Event location, travel times, ellipticity corrections, upper mantle corrections, phase detection, phase recognition

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1 OBJECTIVE

The accurate location and subsequent characterisation of seismic events is a primary requirement of any verification regime for a test ban treaty. Such procedures depend on the use of good models for the propagation of seismic waves and also accurate picks for identified seismic phases.

The objectives of this work are to provide a set of tools which can help with both event location and characterisation. Firstly, through an improved representation of the main radial structure of the Earth and an effective correction procedure for upper mantle heterogeneity. Secondly, through the development of phase detection and recognition procedures which can help with the association of seismic arrivals for use in the location procedures. Thirdly, to try to improve the estimation of the depth of seismic events by integrating knowledge of waveform characteristics with estimation of source character.

2 RESEARCH ACCOMPLISHED

2.1 Earth models for earthquake location

Current methods of locating seismic events depend on the availability of travel-time tables for the major seismic phases which are then supplemented by corrections to allow for lateral heterogeneity within the Earth. Kennett & Engdahl (1991) developed a new radial earth model*iasp91* which was designed for use in event location and phase location by providing a computational summary of observed travel times. The *iasp91* model was best constrained in the mantle and the fits to core phases were not as close as would be desired for optimum utility in location.

New empirical travel-time curves for the major seismic phases, have been derived from the catalogues of the International Seismological Centre by relocating events by using *P* readings, depth phases and the *iasp91* travel times, and then re-associating phase picks for later arrivals. A smoothed set of travel-time tables has been extracted by a robust procedure which gives estimates of the variance of the travel times for each phase branch. This set of smoothed empirical times is then used to construct a range of radial velocity profiles which have been assessed against a number of different measures of the level of fit between the empirical times and the predictions of the models. These measures were constructed from weighted sums ofL_2 misfits for individual phases. The weights have been chosen to provide a measure of the likely reliability of the picks for the different phases. The empirical travel-time information has been supplemented by differential times between the various branches for *PKP* picked from broadband digital records.

A new radial model *ak135* has been proposed (Kennett, Engdahl & Buland, 1995) which gives a significantly better fit to the travel-times for a broad range of phases

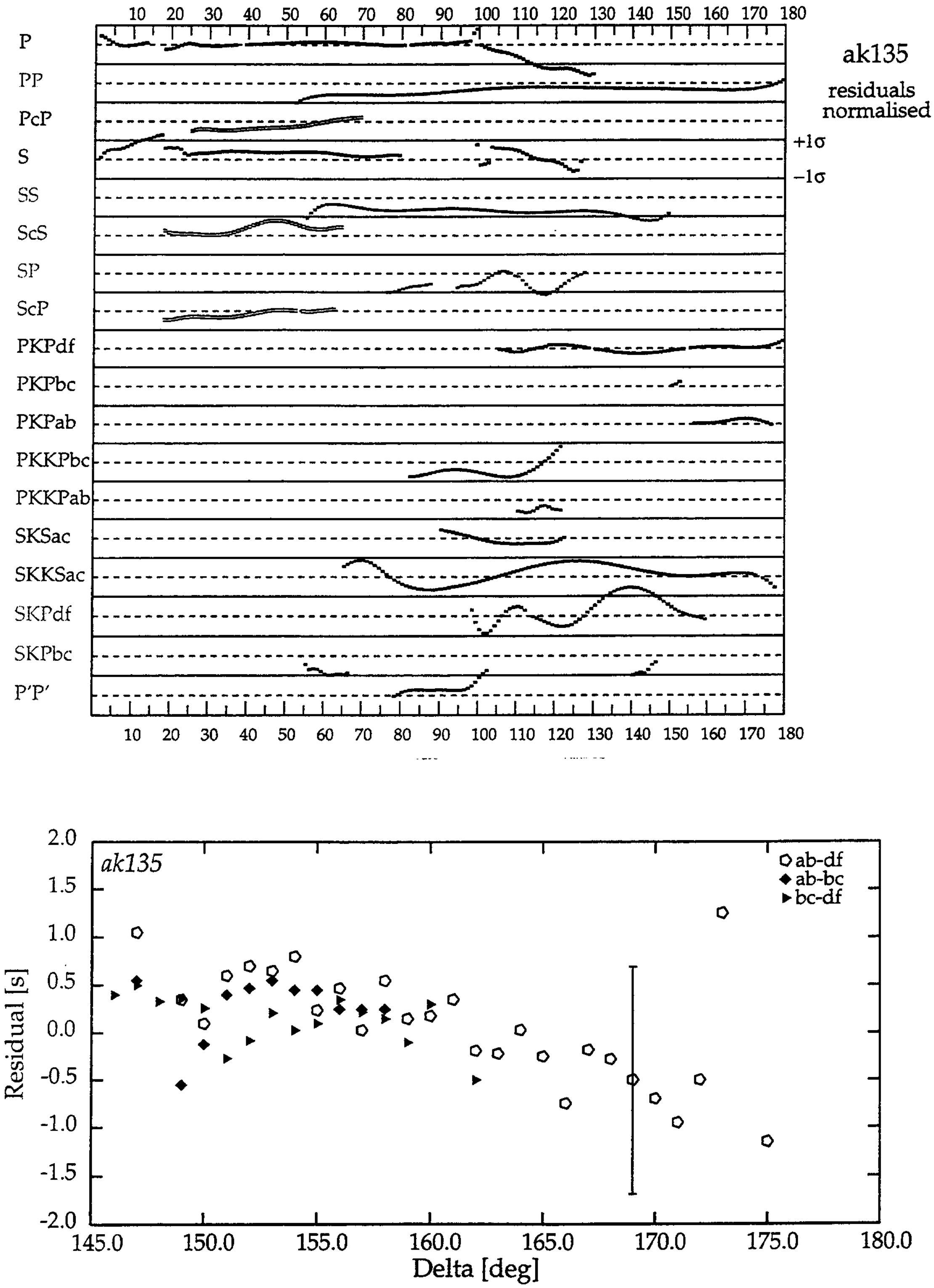

Figure 1. (a) Composite display of the normalised residuals between the travel times predicted for model *ak135* and the smoothed empirical travel times. (b) Differential travel time residuals for core phases for model *ak135* the medians over one degree cells are displayed for each branch.

than is provided by the *iasp91* and *sp6* models. The differences in velocity between *ak35* and these models are generally quite small except at the boundary of the inner core where reduced velocity gradients are needed to achieve satisfactory performance for *PKP* differential time data. The fit achieved with the new *ak135* model to the times for a broad range of phases is illustrated in figure 1, along with the fit to the differential times. A very good fit is achieved to most classes of phases but there are some systematic differences for the surface reflected phases such as *PP*, *SS* and *SP* which are sensitive to the assumptions made about shallow structure. The model *ak135* retains the same class of upper mantle structure as *iasp91* and is oriented towards a continental structure.

The potential resolution of the velocity structure within the Earth from travel-time information has been assessed with the aid of a nonlinear search procedure in which 5000 models have been generated in bounds about *ak135*. Misfit calculations are performed for each of the phases in the empirical travel-time sets and the models are then sorted using different overall measures of misfit. The best 100 models for each criterion are displayed in a model density plot which indicates the consistency of the different models. The interaction of information from different phases can be analyzed by comparing the different misfit measures. Structure in the mantle is well resolved except at the base, and *ak135* provides a good representation of core velocities.

For global use, the travel-times for the various phases need to be corrected for the influence of the ellipticity of the earth on the propagation path from source to receiver. A full set of ellipticity corrections have been tabulated for all the major phases represented in the *iasp* software.

2.2 Corrections for lateral heterogeneity

A radial earth model such as *ak135* provides a good general description of seismic wave propagation, but the presence of lateral heterogeneity within the Earth leads to systematic errors when seismic events are located. Such errors persist even when the geographic distribution of recording stations provide good azimuthal coverage and are particularly pronounced when locations are determined from a limited number of stations. In the likely verification regime of a test ban treaty, it will not be possible to rely on the statistical effects of large numbers of stations as in the current procedures employed by NEIC and ISC at the present time, but instead there needs to be some way of compensating for the major components of lateral heterogeneity. Since the most accurate location procedures will also make use of a wide variety of seismic phases any correction scheme for lateral heterogeneity should be physically based and adaptable to different classes of wave propagation process.

A hierarchical approach to such a correction scheme is being developed in which a total time correction for a phase is assembled from a number of different constituents. For teleseismic events, at least, the dominant lateral heterogeneity arises in the upper mantle and so the upper mantle contributions to both the near-source and near-receiver portions of the propagation path have to be estimated. An initial correction scheme is being based on a regionalised model of the upper mantle based on tectonic character, which exploits recent advances in the representation and interpolation of three-dimensional fields represented via Delaunay tetrahedra. In the regionalised model the structure for each tectonic province is represented via a radial velocity model and smooth interpolation occurs across a transition zone between regions. Ray-tracing

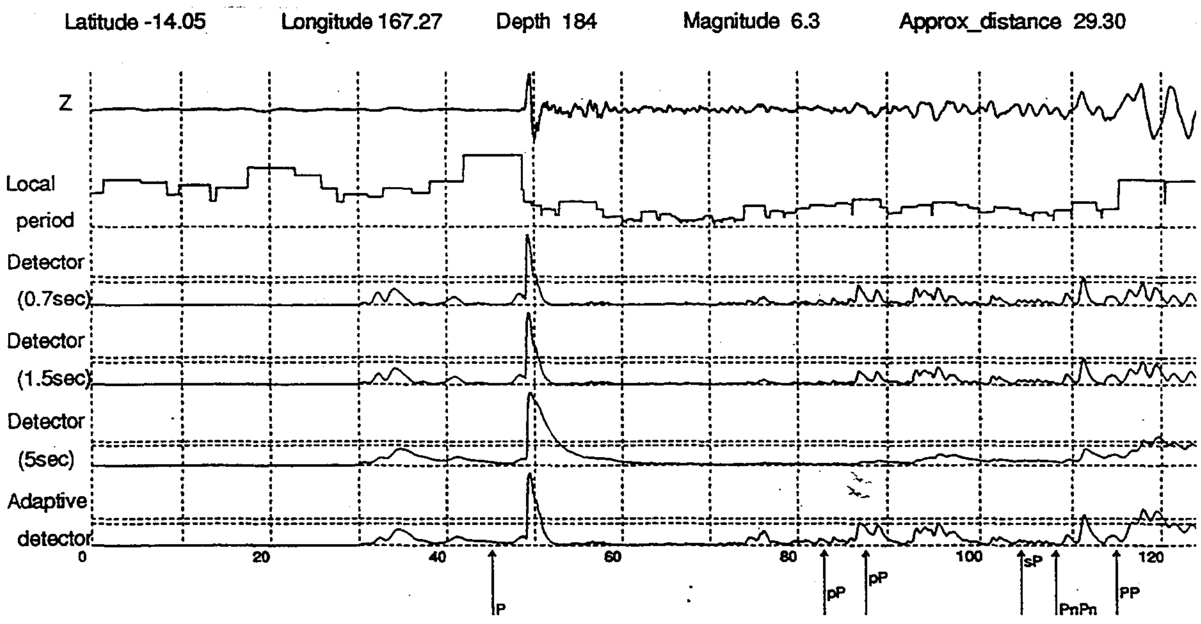

Figure 2. Comparison of phase detectors based on fixed window lengths with an adaptive detector exploiting information on local frequency.

through this simple model provides source-end and receiver-end corrections for upper mantle structure for either *P* or *S* wave legs. Superimposed on these corrections we can then have station specific terms designed to compensate for crustal structure or station elevation.

2.3 Phase recognition

The location of seismic events can be improved if accurate picks can be assigned for later seismic phases, which requires both the detection of an arrival and the recognition of its character. Such phase identifications are particularly valuable if they can be provided in real-time as the seismic disturbance passes across a broadband seismic recording station.

This problem of automatic phase recognition plays an important role in seismogram interpretation, especially in the context of the rapid analysis of large volumes of data in a verification regime. Two different pattern recognition problems are involved. Firstly, we need to separate seismic signals from background noise; then we try to recognise the difference between phase wavelets. Due to the wide range of frequencies for different phases in a broadband seismogram, phase recognition is a context sensitive problem.

An automatic analyzer has been developed which is adaptive to the local waveform background (Tong 1995). The analyzer works on single seismic components using concepts from work in artificial intelligence (especially pattern recognition (Tong, 1995). A seismogram is recognised as a hierarchical structure of subunits - waveform segments - and the features characterising a phase are extracted via a structural analysis.

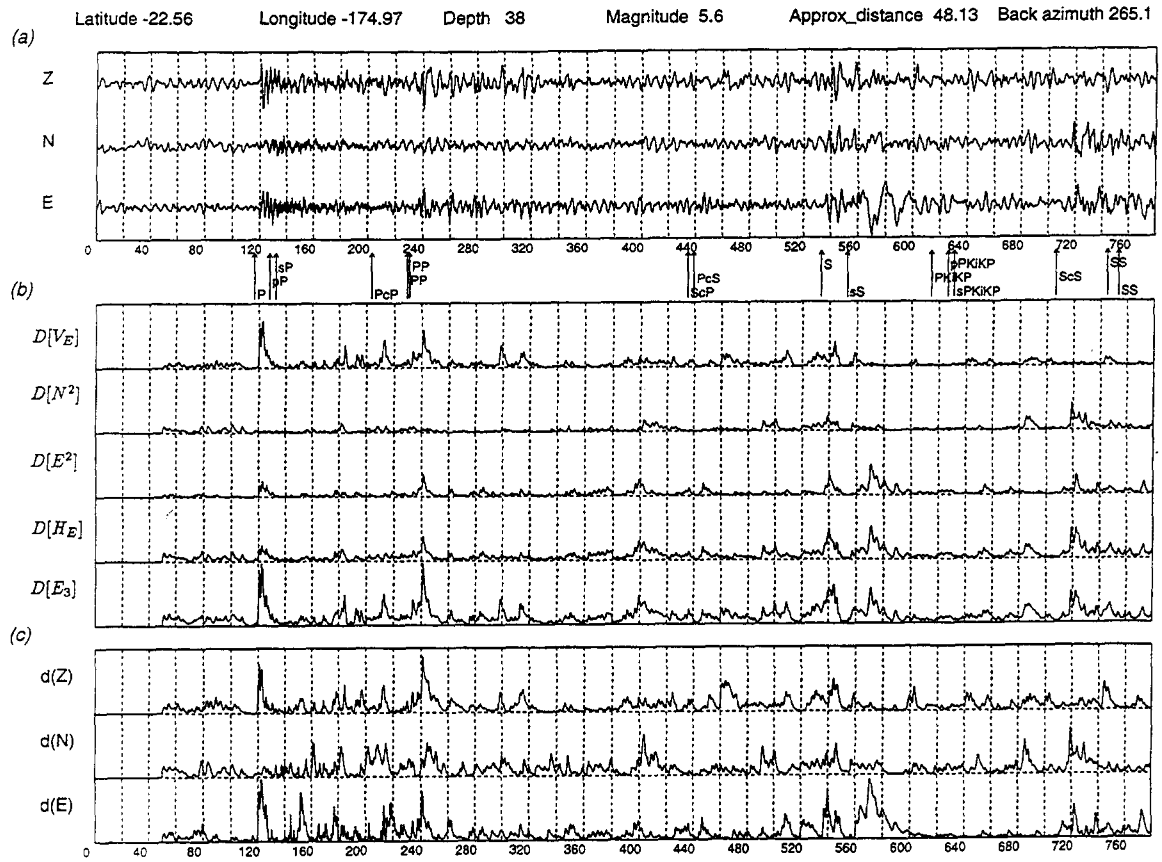

Figure 3. Analysis of broadband records for a shallow Kermadec event recorded in Northern Australia (time scale in seconds): (a) unfiltered broadband records, with indications of the predicted times for phase arrivals using the *iasp91* traveltime tables, (b) phase detectors based on an LTA measure based on total energy and STA measures for various energy contributions from the three-component traces, (c) single component STA/LTA detectors applied to each of the three components separately.

The automatic analyzer recognises the contiguity of an appropriate set of waveform segments and uses this to assign an estimate of the local frequency on the seismic trace. This local frequency information is then used to update the parameters of an STA/LTA phase detection procedure (Fig 2). Following a detection, the pattern recognition analysis separates out the phase contribution by the pattern of waveform segments and then attempts to characterise the extracted phases with a standard Gabor wavelet described by a set of five parameters. The whole analysis procedure requires just a few input parameters and can be accomplished swiftly enough to allow continuous real-time operation.

The analysis procedure is adaptive and can be successfully applied to broadband records with a wide range of frequency content. By coupling the analysis procedure with real time filtering very good results for phase detection and characterisation can be

achieved for weak distant events. The characterisation of phase segments also provides useful information for the comparison of seismograms and is being investigated as a tool for the comparison of observed and synthetic seismograms.

A simple but promising scheme for identifying the physical character of phase arrivals can be constructed by analysing the energy content of the seismic trace as a function of time (Tong & Kennett, 1995). This approach can be used to detect arrivals by comparing the short-term average energy to a long-term average, with averaging windows that are adaptive to the local frequency of the seismic disturbance based on the use of real-time pattern recognition applied to the seismic traces. The phase detector can be tuned to different classes of arrivals by utilising three-component records (fig 3). By comparing the energy on the vertical component of motion to that in the horizontal plane, it is possible to start to separate *P* and *S* arrivals. Phase assignments can be refined by the use of adaptive filtering and by including polarisation information.

With an estimate of the azimuth of propagation it is possible to use approximate projection methods which attempt to compensate for the influence of the free surface (Kennett 1991), since the surface corrections are not a strong function of slowness for teleseismic arrivals. By this means an instantaneous estimate can be made of the relative contributions of *P, SV* and *SH* arrivals which can be very helpful in determining the phase assignment for a particular arrival.

3 FUTURE PRIORITIES

The priorities for future work are to refine location procedures to provide a rapid means of including the influence of lateral heterogeneity within the Earth, and to improve constraints on depth estimation especially for shallower events where the depth phases are not distinct.

The use of regionalised models represents a starting point for a more realistic representation of three-dimensional structure within the upper mantle, derived from a tomographic style inversion. A lower resolution global inversion coupled to a high resolution representation of subduction zones is currently being undertaken to study subduction zone structure but can be readily adapted for location studies. A interesting problem is the appropriate way of filtering the velocities derived from tomography to provide the most effective model for location. It will also be necessary to introduce a priori information in those regions of the upper mantle such as much of the ocean basins for which current sampling by propagation paths are inadequate. Rapid ray-tracing procedures for three-dimensional models will be based on the Delaunay tessellation procedures used to represent the heterogeneous models to allow the testing of simpler correction procedures based on perturbation theory.

For the problem of depth estimation, the most promising route is to make use of comparisons between observed and synthetic seismograms. However this requires an adequate knowledge of the source mechanism. For larger events a number of different techniques can be employed to obtain a point source description of a source. However, for small shallow events the potential resolution of the source mechanism is limited. The inversion procedure needs to couple the source mechanism and depth problem and to try to obtain multiple constraints by exploiting the waveforms and relative amplitudes of many different phases.

ACKNOWLEDGEMENTS

The work in this report has been accomplished by a number of the Seismology Group notably Cheng Tong, Brian Kennett, Oli Gudmundsson and Malcolm Sambridge.

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